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RUGGED, THIN GaAs SOLAR CELL DEVELOPMENT

APPLIED SOLAR ENERGY CORPORATION
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THIS REPORT DESCRIBES THE PHASE II EFFORTS IN DEVELOPING HIGH EFFICIENCY GaAs-ON-Ge SOLAR CELLS FOR ENHANCED SURVIVABILITY, RUGGEDNESS, AND REDUCED WEIGHT OVER CONVENTIONAL DEVICES. THIS WORK EMPHASIZES EFFORTS TO IMPROVE THE CELL PERFORMANCE FROM PHASE I, INITIAL TESTING OF THE CELLS, AND FABRICATION OF A MODULE FOR SPACE FLIGHT TESTING.

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1.0 INTRODUCTION

The overall objective of this program is to develop the technology for fabricating thin layer, high-efficiency GaAs solar cells using thin germanium substrates (*76 micrometers*). The specific goals for the program are:

- An Air Mass Zero (AMO) conversion efficiency of 18% for beginning-of-life (BOL) at 27 $\pm$ 2°C.
- An AMO conversion efficiency of 13.5% at 27 $\pm$ 2°C after exposure to 5×10^{15} (MeV) electrons/cm^2.
- A cell weight not to exceed 0.05 grams per square centimeter of cell area.

The overall program consists of three phases:

1) Phase I - Cell Fabrication
2) Phase II - Cell Optimization
3) Phase III- Cell Testing

In Phase I of the program, it was demonstrated that the conversion efficiency of a 2x2 cm GaAs/Ge solar cell reached 16.4% under AMO and at 28°C. The open-circuit voltage, Voc, was 1.113 V; the short-circuit current, Isc, 113.2 mA; and the fill-factor, CFF, 0.705. The cell thickness was in the range 8-10 mils. Comparing these cell parameters with those of typical GaAs cells on GaAs substrates, it was found that the fill factors of the GaAs/Ge cells were much lower than those of the GaAs on GaAs cells. The typical light I-V characteristics of the GaAs/Ge cells, as shown in Figure 1, indicates that the low CFF of the cell is due to series resistance. The main efforts in Phase II of the program were to understand and improve the fill factor of GaAs/Ge

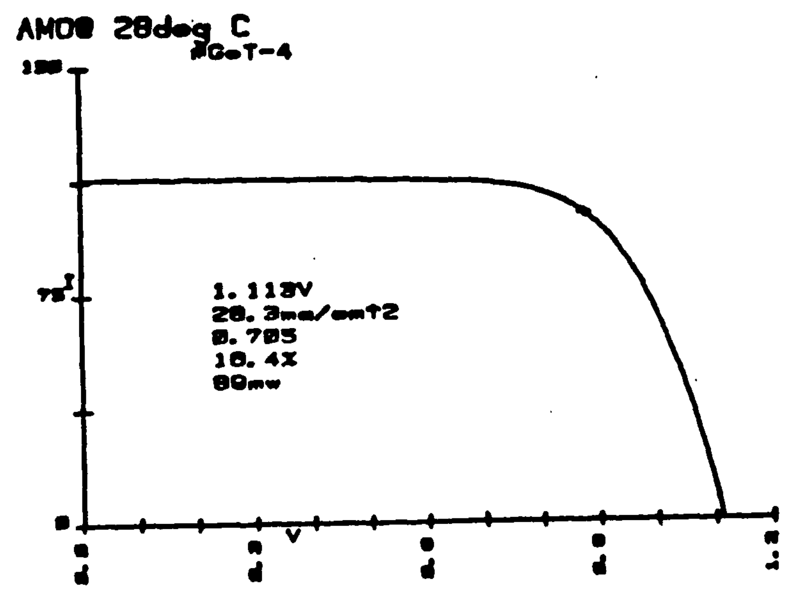


FIGURE 1. Light I-V characteristics of a GaAs/Ge solar cell made during Phase I of the program.

cells and to reduce the weight of the cell by further thinning the Ge substrates.

2.0 FILL-FACTOR IMPROVEMENTS

Since it has been found that the low CFF of the GaAs cells was due to the series resistance of the cell, both the p-contact and n-contact resistances were evaluated and found to be about 10^{-5} ohm-cm^2; too low to cause any series resistance problem for the cell. Typical fill factors of conventional GaAs on GaAs cells grown and processed at the same time were of order 0.80. These results indicate that the series resistance of the GaAs/Ge cells is not caused by the ohmic contacts. The other principal source of cell resistance is the isotype heterojunction between the Ge substrate and the n-type GaAs buffer layer.

An evaluation of the n-GaAs/n-Ge interface was performed. Several as-grown AlGaAs/GaAs solar cells on Ge substrates were etched in a 3:1:1 H_2S0_4: H_20_2:H_20 solution to remove the (p)AlGaAs and (p)GaAs layers. The remaining structure was an n-type GaAs buffer layer on the n-type Ge substrate. N-type ohmic contacts were formed on both sides of the structure and the samples were cut into 5x5 mm squares to measure the electrical properties of the GaAs/Ge interface.

Figure 2 shows the dark I-V characteristics of a 5x5 mm (n)GaAs/(n)Ge isotope heterojunction. The back contact on the backside of the (n)Ge was grounded and the n-contact on (n)GaAs was biased positively (or negatively) with respect to the ground. The I-V curve was non-linear and the resistance value was 2 ohm near the origin. The same samples of 0.5 cm square in size

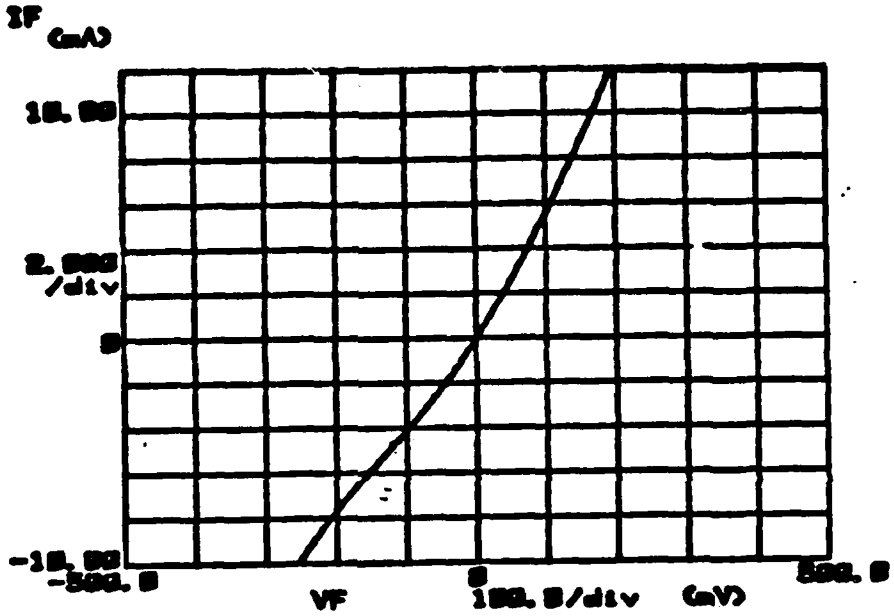


FIGURE 2. Dark I-V characteristics of a (n) GaAs/(n)Ge isotope heterojunction. The size of the device is 5 mm square.

were tested under the AMO simulator. It was found that the open circuit voltage was 0.03 V and that the short-circuit current was 2.8 mA (without AR coating). The polarity of this Voc is in the same direction as that of the p on n GaAs solar cell. This result suggests that band bending occurs at the GaAs/Ge interface in a manner to separate charge resulting in both a photovoltaic effect and increased series resistance thus both raising Voc and lowering the fill factor.

The doping profile of a GaAs homojunction grown on a Ge substrate, as measured with a Polaron C-V profiler, is shown in Figure 3. The flow of the H_2Se dopant was set to provide a base doping of 1-2 x 10^{17} cm^{-3} during conventional growth on a GaAs substrate. As can be seen, the first 6 um is doped to 2 x 10^{18} cm^{-3}; the excess impurities apparently due to out-diffusion of Ge at the 720C growth temperature. The last 3 um of the base were grown at 680C and the doping dropped to 2 x 10^{17} cm^{-3} as the Ge diffusion is suppressed.

2.1 Metal Interconnection Between GaAs and Ge

One possible way to reduce the resistance between the Ge substrate and the n-type GaAs buffer layer is to insert a metallic contact at the interface. As Au/Ge is a good ohmic metal system for n-type GaAs, as well as a refractory metal, stable at MOCVD growth temperatures, it was attempted to use Au as a interconnecting ohmic metal between the Ge and (n+)GaAs buffer layer. The experiment was carried out by depositing and defining 300A thick Au strips on the n-type Ge wafers. Au/Ge alloy was formed by sintering the sample at 450^{o}C in forming gas. The wafer was then loaded into the MR200 reactor to grow the GaAs cell structure. The resistivity of the Ge substrate was 0.8

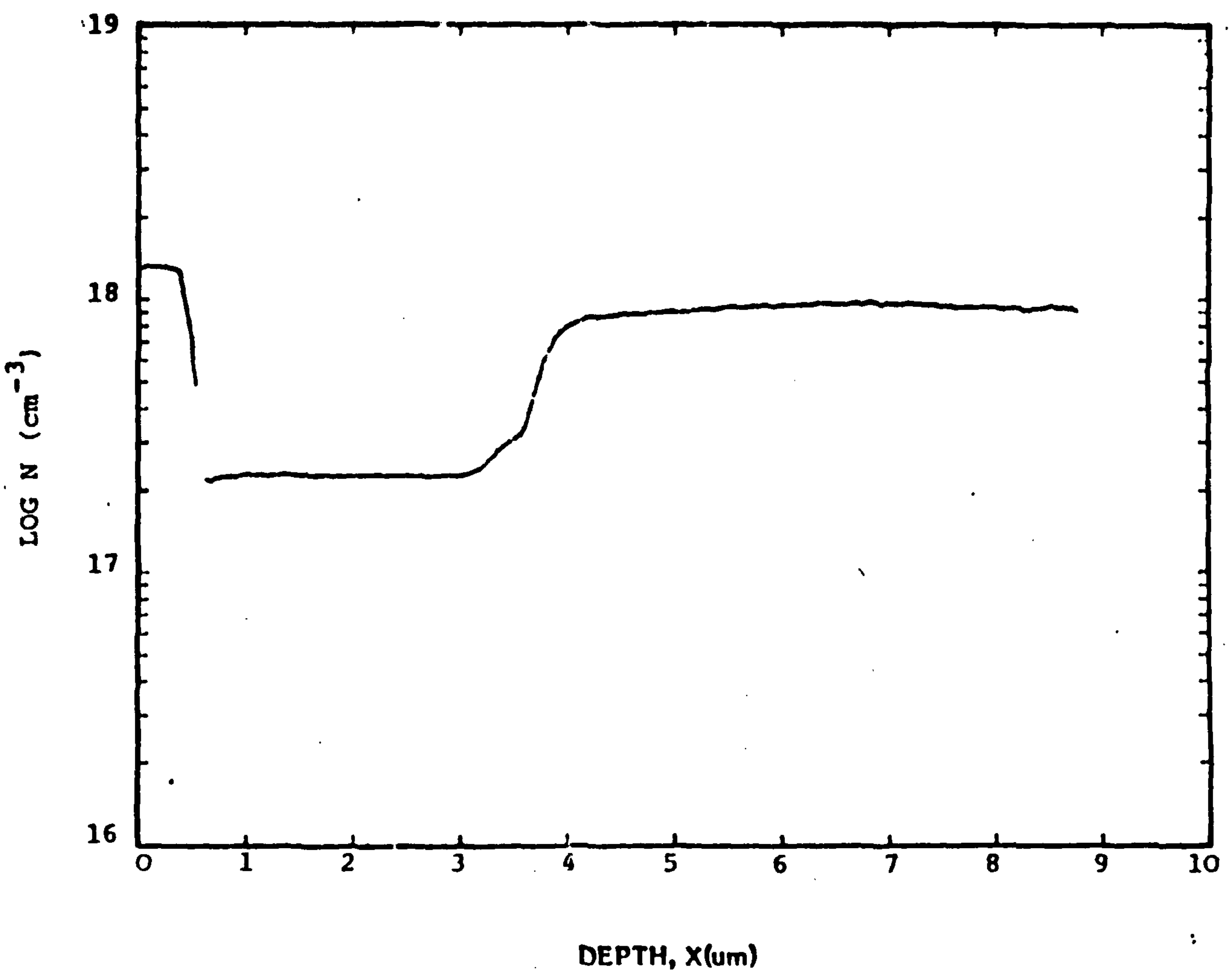


FIGURE 3. Doping profile of a GaAs P/N junction grown on a Ge substrate.

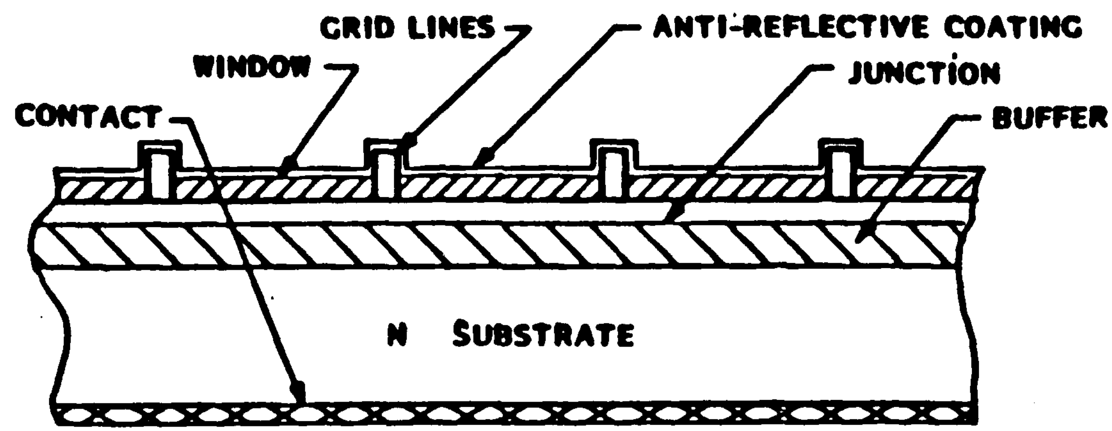
ohm-cm. After growth, the surface morphology on top of Au/Ge alloy was rougher than that over the normal areas. The resistance between the (n)GaAs buffer layer and the Ge substrate was negligible, but the open-circuit voltage was also diminished. The low Voc was apparently due to poor quality of the epitaxy grown on the Au/Ge alloy.

3.0 PROCESSING OF GaAs/Ge SOLAR CELLS

The complete structure of the heterostructure GaAs/Ge solar cells is shown in Figure 4. A 6-7 mil thick Ge wafer was loaded into MOCVD reactor and a p-on-n GaAs homojunction with a p-type AlGaAs window was grown. The n-type buffer layer was about 9 um thick; the p-type GaAs emitter 0.45 um; and the window layer 0.1 um thick. After layer growth, the standard Au/Zn/Ag p-conctact was formed on the front surface using lift-off techniques. A double layer AR coating was then deposited and sintered. The front contacts were formed first to reduce the complexity of thinning the Ge wafer and to improve the mechanical yield of the overall process.

The cells were then thinned to 3-4 mils to meet the goal of the 0.05 gram/cm^2. Several chemical systems were explored to find a fast and uniform etchant. H_2O_2 at both 22^oC or 70^oC was investigated. The initial etch rate of this solution was fast and the etch rate dropped rapidly after half an hour of usage.

The back contact was deposited and sintered after the wafer was thinned to the desired thickness. The back contact consists of Au/Ge/Ni/Ag because Au and Ge forms good eutectic alloy and also forms a good ohmic contact to n-



ELEMENT	THICKNESS (μm)	COMPOSITION	DOPANT CONCENTRATION (x 10^{18} cm^{-3})
GRID (p-CONTACT)	4.4	Ag – Au Zn Au	–
AR COATING	0.1	TiO_x/Al_2O_3	–
WINDOW (p^+)	0.1	$Al_xGa_{1-x}As$ (Zn)	2 TO 4
JUNCTION (p)	0.45	GaAs (Zn)	2
BUFFER (n)	9	GaAs (Se)	0.2 TO 0.5
SUBSTRATE (n^+)	75	Ge (Sb)	–
n – CONTACT	3.38	Ag – Au Ge Ni Au	–

FIGURE 4. GaAs/Ge Solar Cell Structure

1. THIN Ge SUBSTRATES TO 7-8 MILS.
2. PREPARE THE SURFACE OF Ge WAFERS.
3. GROW GaAs AND AlGaAs BY MOCVD TECHNIQUE.
4. ETCH WINDOW LAYER.
5. DEPOSIT FRONT P-CONTACTS.
6. DEPOSIT AR COATING.
7. THIN GaAs/Ge CELLS TO 3 MILS.
8. DEPOSIT BACK n-CONTACTS
9. CUT CELLS TO SIZE.
10. TEST

FIGURE 5. Process Steps for Thin GaAs/Ge Solar Cells

type GaAs. Finally, the cells were cut into size and tested. The cell processing flow chart is shown in Figure 5.

As discussed in Section 2.0, the fill factor of the cell strongly depends on the electrical properties of the inteface between the (n+)GaAs buffer layer and the Ge substrate. It is desirable to reduce the barrier height and/or thin the barrier width to obtain linear I-V characteristics with low resistance. Besides the metal interconnecting approach, as was mentioned in Section 2.1, another approach is to use Ge substrates with lower bulk resistivity. Ge wafers with resistivities as low as 0.014 ohm-cm, about 60 times lower than that of the previous Ge wafers were obtained. These wafers were processed to evaluate the affect on fill factor but they were not thinned down to 3-4 mils. Table 1 lists the performance of the cells. The left side of the table lists the performance of each individual cell and the right side of the table shows the cummulative average cell performance. It is noted that the best cell efficiency reached 17.1% under AMO at $28^{o}C$ with a fill factor of 0.742. At the 50% yield point, the average fill factor was 0.722 and the efficiency was 16.8%. These fill factors are higher than those of the cells made form the high resistivity Ge wafers. The results confirm that the interface between (n+)GaAs and (n)Ge can be lowered and/or thinned using low resistivity Ge wafers.

The illuminated I-V characteristics of the cells listed in Table 1 are shown in Figures 6 through 17.

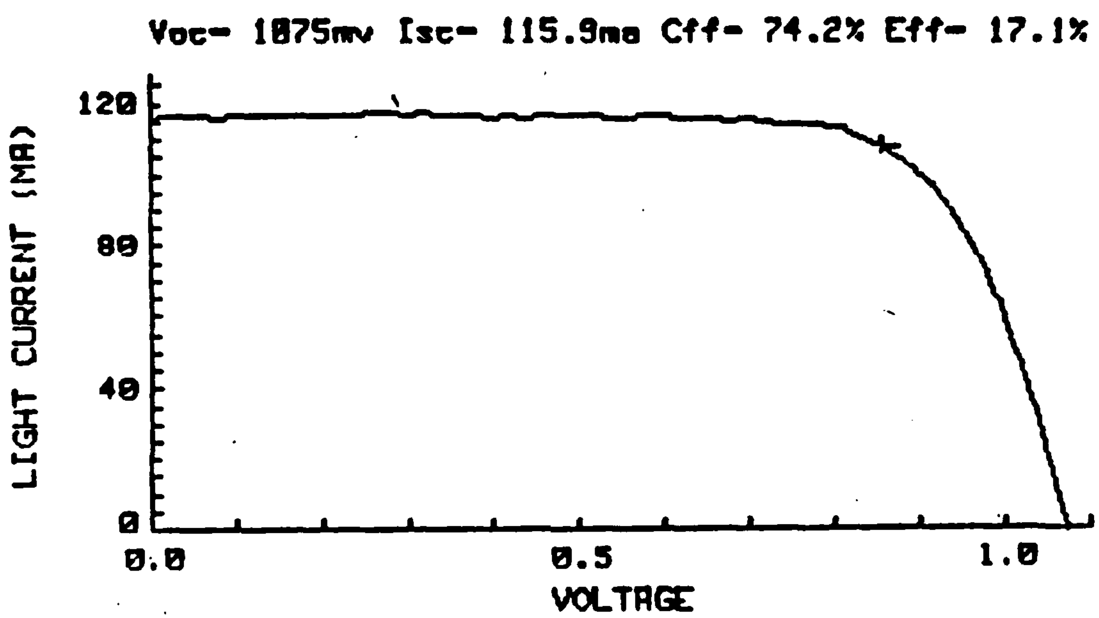
4.0 SPIRE MACHINE EVALUATION

Two MOCVD runs in the low pressure, Spire 450 reactor, were made in March, 1988. In each run, a Ge wafer and four GaAs wafers were loaded on the five-

TABLE 1

PERFORMANCE OF 2X2 cm GaAs/Ge SOLAR

Cell #	Voc (mV)	Isc (mA)	CFF (%)	Vm (mV)	EFF (%)	Yield (%)	Voc (mV)	Isc (mA)	CFF (%)	Vm (mV)	EFF (%)
12	1075	115.9	74.2	856	17.1	8.3	1075	115.9	74.2	856	17.1
5	1101	115.1	72.0	856	16.9	16.7	1088	115.5	73.1	856	17.0
2	1091	116.6	71.7	860	16.8	25.0	1089	115.9	72.6	857	16.9
6	1092	115.2	72.5	864	16.8	33.3	1090	115.7	72.6	859	16.9
7	1083	116.1	71.8	856	16.7	41.7	1088	115.8	72.4	858	16.9
4	1094	115.5	71.2	824	16.6	50.0	1089	115.7	72.2	853	16.18
1	1092	115.5	71.1	868	16.6	58.3	1090	115.7	72.1	855	16.8
9	1098	116.4	70.0	856	16.5	66.7	1091	115.8	71.8	855	16.8
11	1061	116.3	72.0	828	16.4	75.0	1087	115.8	71.8	852	16.7
10	1096	113.3	70.9	864	16.3	83.3	1088	115.6	71.7	853	16.7
3	1080	116.8	693	828	16.2	91.7	1088	115.7	71.5	851	16.6
8	1088	115.1	69.1	824	16.0	100.0	1088	115.6	71.3	849	16.6



<u>FIGURE 6.</u> Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#12) tested under AMO.

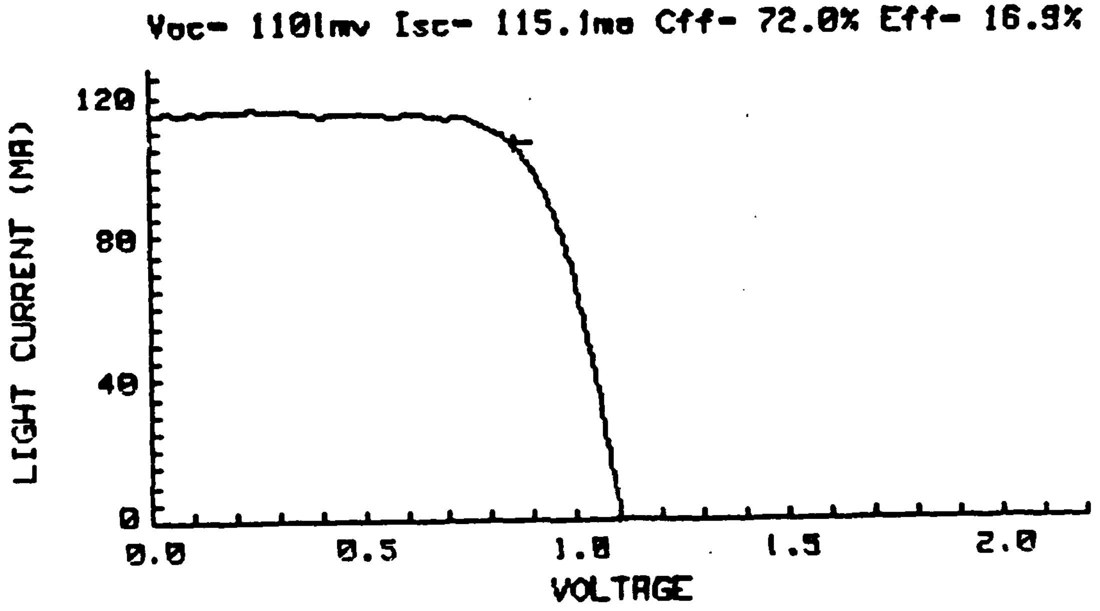


FIGURE 7. Light I-V curves of a 2 x 2 cm P on N GaAs/Ge solar cell (#5) tested under AMO.

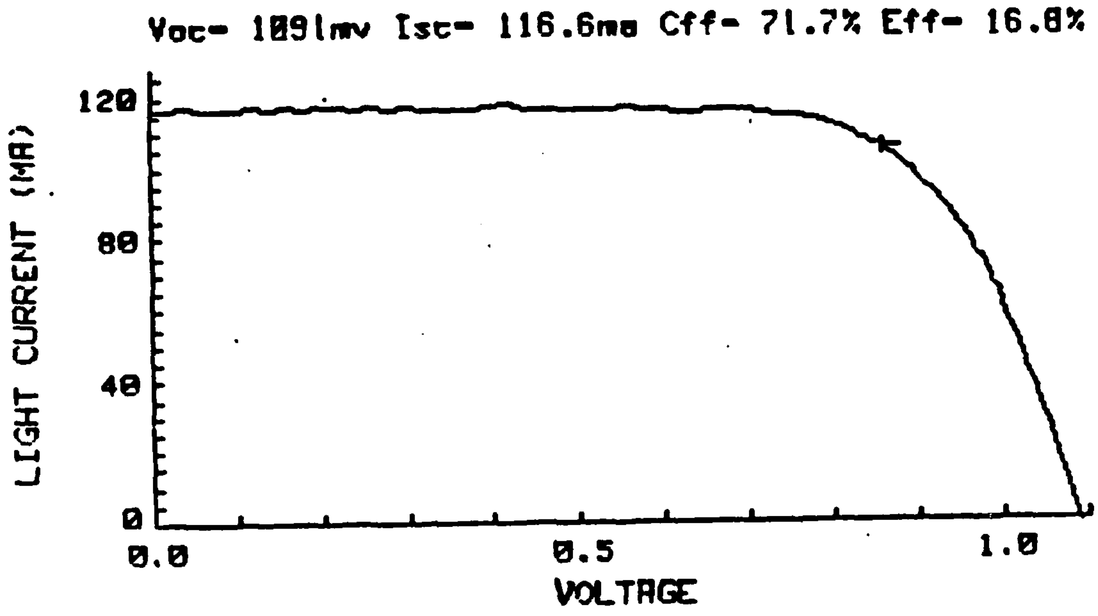


FIGURE 8. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#2) tested under AMO.

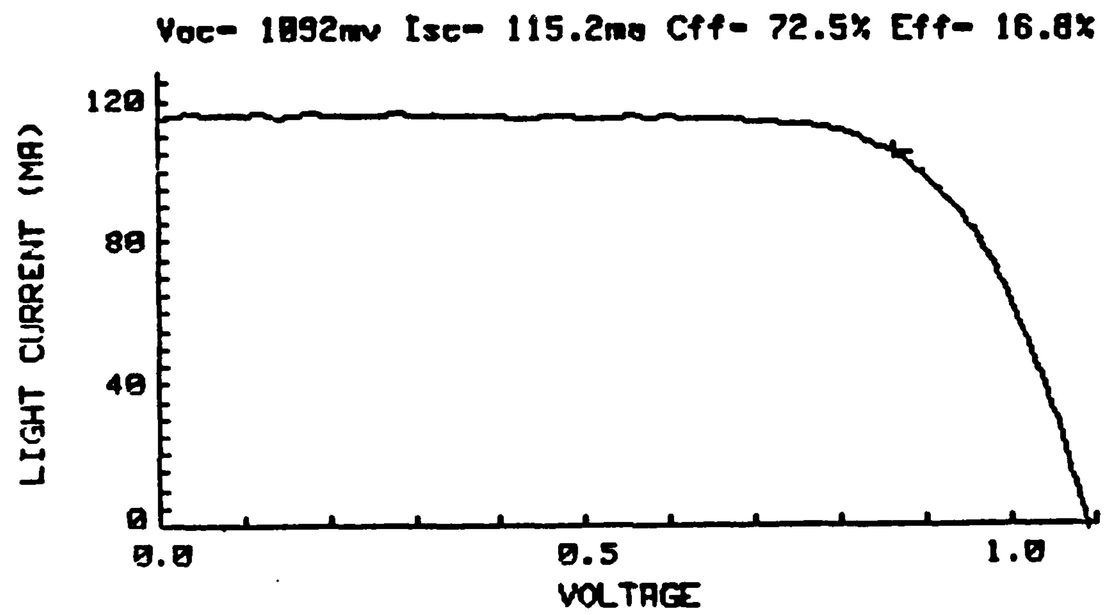
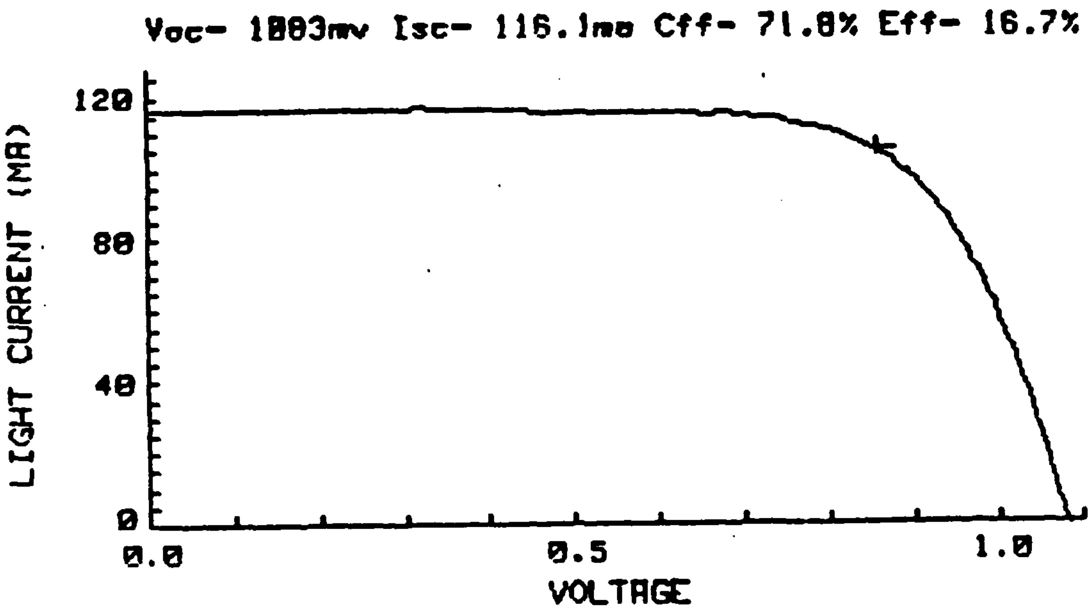


FIGURE 9. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#6) tested under AMO.



<u>FIGURE 10.</u> Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#7) tested under AMO.

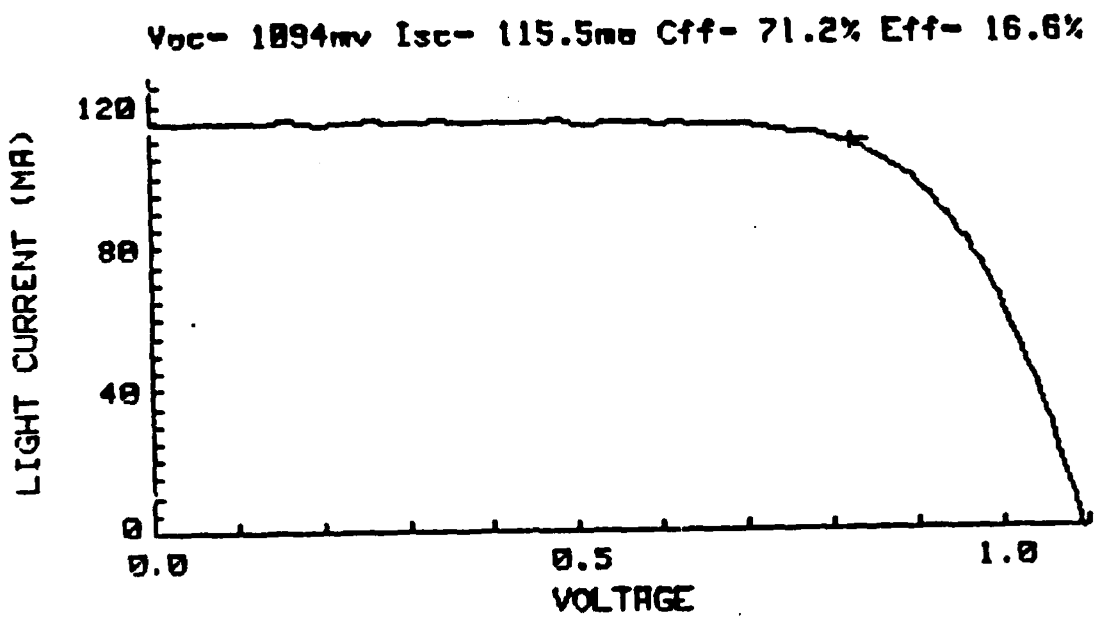


FIGURE 11. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#4) tested under AMO.

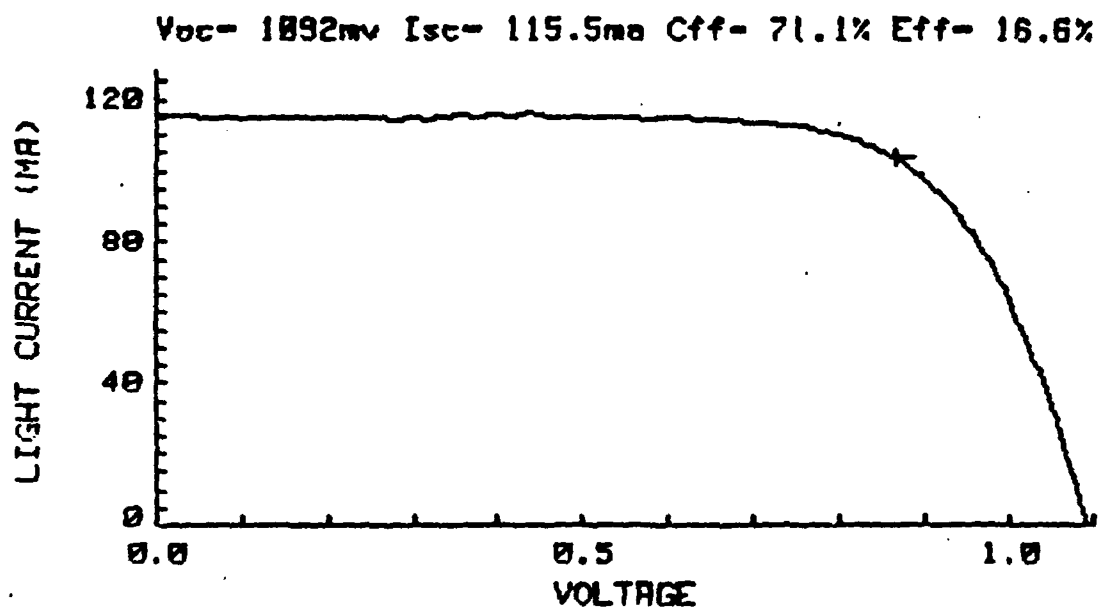


FIGURE 12. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#1) tested under AMO.

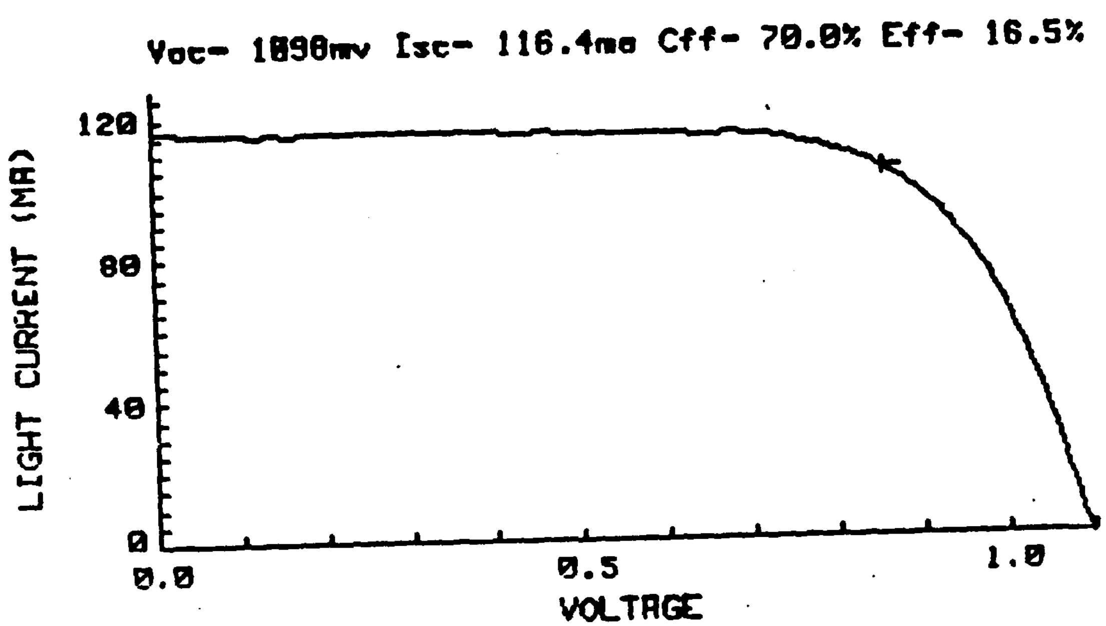


FIGURE 13. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#9) tested under AMO.

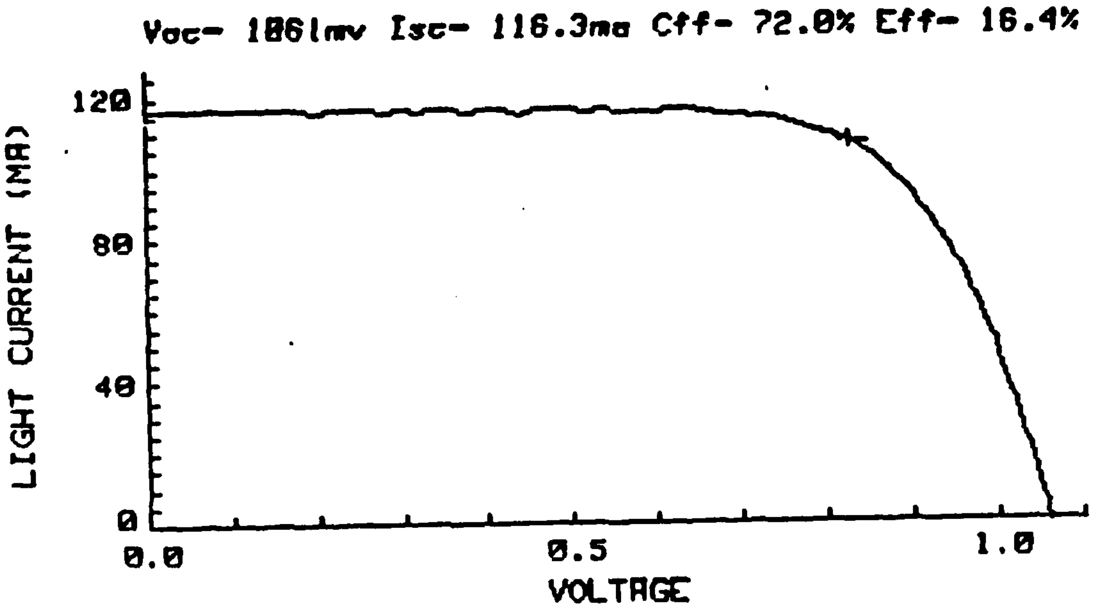


FIGURE 14. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#11) tested under AMO.

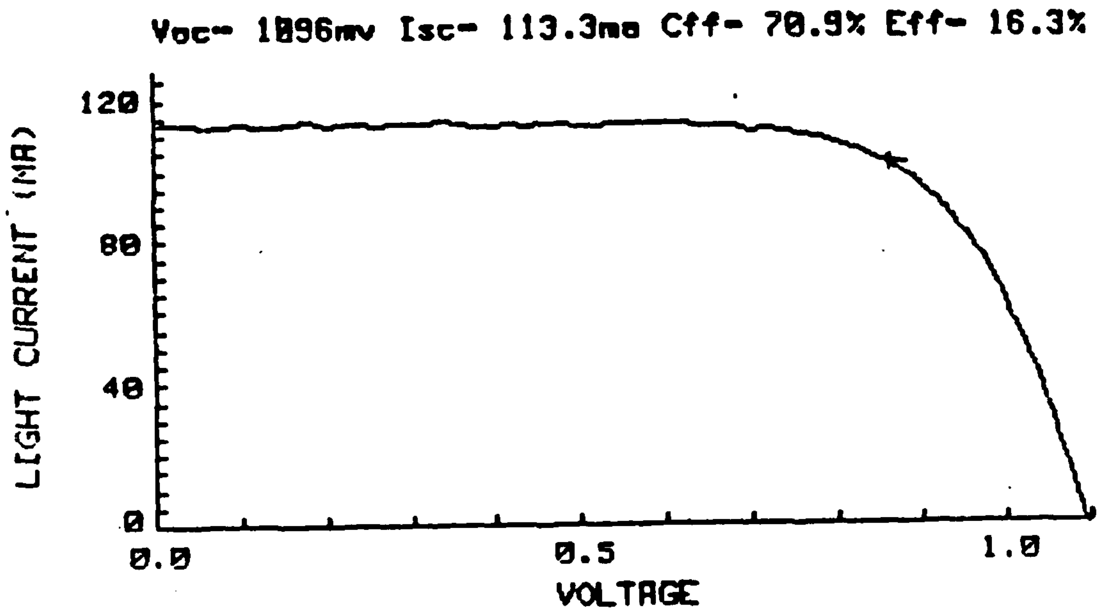


FIGURE 15. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#10) tested under AMO.

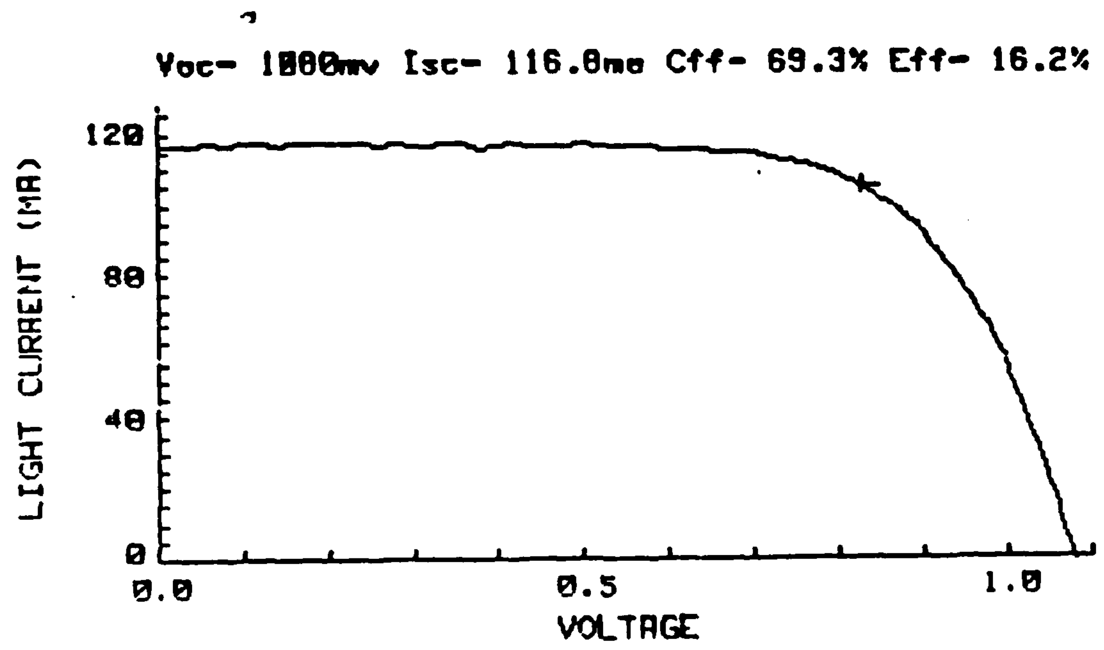
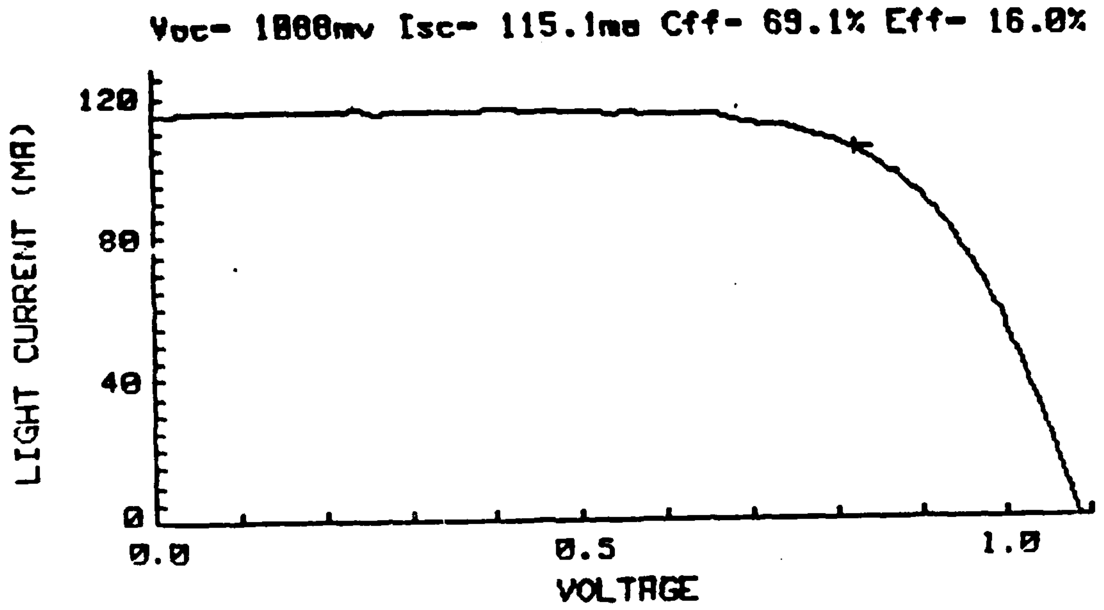


FIGURE 16. Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#3) tested under AMO.



<u>FIGURE 17.</u> Light I-V curves of a 2x2 cm P on N GaAs/Ge solar cell (#8) tested under AMO.

TABLE 3

PERFORMANCE OF 2X2 cm GaAs/ Ge CELLS AND GaAs CELLS

BEFORE AR COATINGS

Cell #	Voc (mV)	Isc (mA)	CFF (%)	n (%)	Substrate
1	610	65.2	56	4.1	Ge
2	619	66.2	59	4.5	Ge
3	934	69.5	76.4	9.2	GaAs
4	935	69.4	76.8	9.2	GaAs
5	968	69.6	71.5	8.9	GaAs
6	960	71.9	76.3	9.7	GaAs
7	962	73.0	78.1	10.1	GaAs

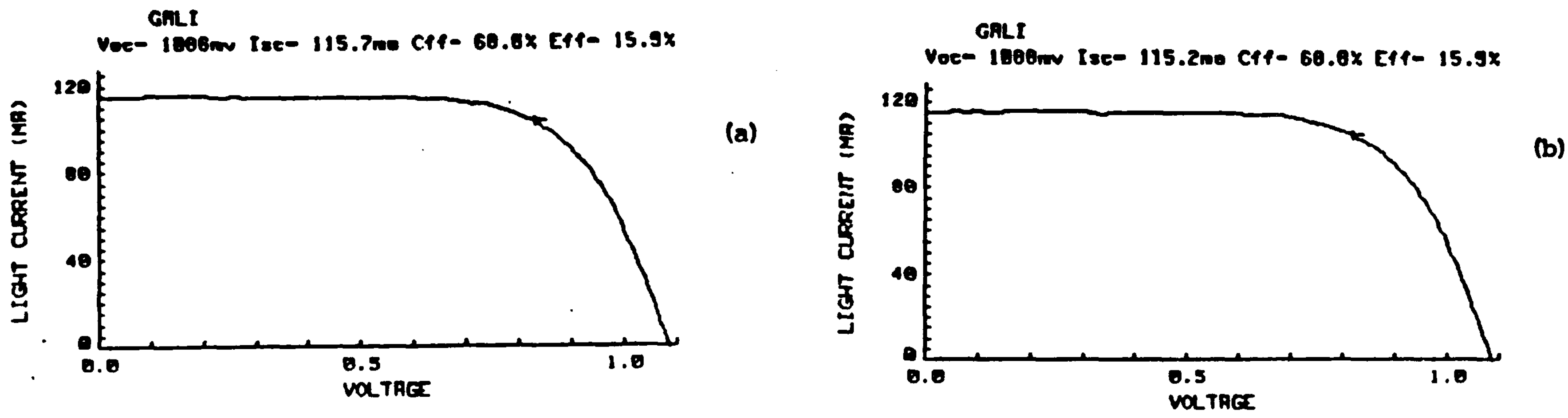
faceted susceptor. Table 2 lists the growth conditions of each run. The run was performed at 800^{o}C and the as-grown layers on Ge were polycrystalline. This is believed to be caused by the high growth temperature and low growth pressure. This growth temperature may be right to grow high quality AlGaAs, but it was too close to the melting point of Ge; 937^{o}C at one atmosphere.

Another run was carried out at 650^{o}C. Better epitaxial layers on the Ge substrates were obtained and 2x2 cm cells were made on these wafers. Table 3 lists the cell performance under AMO before AR coating. The open circuit voltages, Voc of these cells were about 610 mV and the fill-factor was less than 60%. The low Voc was believed to be due to the quality of the initial growth at the Ge and GaAs interface, because the GaAs cells made on the GaAs substrates grown in the same MOCVD run had an average Voc of 952 mV. The poor CFF of the GaAs/Ge cells was due to the non-linear I-V characteristics of the (n)GaAs/(n)Ge isotype interface as discussed before.

5.0 <u>SOLDERABILITY</u>

Technical effort for June emphasized making interconnects to the 2x2 cm GaAs/Ge solar cells. The first attempt was to solder the tabs onto the ohmic pads on the front p-contacts. SN62 solder paste was applied to the ohmic pads of the cell and the cell was heated on a belt to re-flow the solder. A silver-plated tab was connected to the ohmic pad using a Unitek soldering machine.

Two tabs were soldered to the pads of GaAs/Ge cell #8 whose conversion efficiency was 16.0% under AMO. No degradation in the electrical performance of the cell was observed after soldering. Figure 18 shows the



<u>FIGURE 18.</u> Light I-V characteristics of a GaAs/Ge solar cell #8 (a) before and (b) after soldeirng tabs to the front P-ohmic contacts.

illuminated I-V characteristics of the cell after soldering. The tabs on the cell were then pulled at 45 degrees with respect to the cell surface. The results of the pull test were 925 and 475 grams for the right pad and the left pad, respectively. This pull strength was acceptable because they are higher than 250 grams which was the criteria for pass/fail of the test for the GaAs solar cell Mantech program. Also, the failure mode of the test was due to large divots in GaAs not due to GaAs and Ge separation.

6.0 PROGRAM STATUS

A paper summarizing the current results of this program has been prepared for the SPRAT conference at NASA-Lewis on 7th October 1986. A copy of this paper "Hetero-Structure Solar Cells" is attached to the report (The Appendix).

The 12 2x2 cm GaAs/Ge solar cells reported in July and two cells made in September were used to make a panel. The cells made in September had better fill factor (77%) but slightly lower Voc. These cells were first soldered with tabs and then the cover glass was mounted. Two kinds of cover glasses were used. One coverglass was 4 mil thick and the other 6 mil. Figure 21 shows the cells mounted on a panel. Two strings (1 and 2) and two individual cells (3 and 4) were made of GaAs/Ge cells. The cells in string 1 were covered with 4 mil thick coverglass. Other cells were covered with 6 mil thick coverglass.

Table 4 lists the cell performance at each assembly stage. The first column lists the cell performance before soldering; the second column the cell performance after soldering; the third column the parameters after glassing;

and the last column the parameters after mounting on the panel. There was slight improvement in cell performance after soldering and glassing. The second cell and the fourth cell in string 2 degraded after mounting on the panel. Therefore, only the first cell in String 2 remained on the panel and other three cells in the string were removed. The two cells fabricated in September were located at the fourth cell in String 1 and the first cell in String 2.

TABLE 4

CELL PARAMETERS AT EACH STAGE OF THE ASSEMBLY PROCEDURE

CELL#	BEFORE SOLDERING Voc(mV)	BEFORE SOLDERING Isc(mA)	AFTER SOLDERING Voc	AFTER SOLDERING Isc	AFTER GLASSING Voc	AFTER GLASSING Isc	AFTER MOUNTING Voc(mV)	AFTER MOUNTING Isc(mA)	REMARKS
12	1075	115.9	1079	118	1080	117	1080	119	Cell #3 on the panel.
2	1091	116.6	1094	118	1094	119	1094	117	Cell #4 on the panel.
6	1092	115.2	---	---	---	---			Cell shunted after soldering.
7	1083	116.1	1076	117.2	1081	119			
4	1094	115.5	1099	116	1102	119	4280	115	String I on the panel.
1	1092	115.5	1096	117	1096	118			
9	1098	116.4	1101	118	---	---			Front tab broke after glassing.
11	1061	116.3	1046	118	1051	117			
10	1096	113.3	1100	114	1105	116			
8	1088	115.1	1093	116	1093	115			
9-1	945	111	945	111	945	116			Cell on String 1.
9-3	951	112	951	112	950	120			Cell remained on String 2

FIGURE 21. (Only #1 cell left on plate.)

APPENDIX

HETEROSTRUCTURE SOLAR CELLS

HETEROSTRUCTURE SOLAR CELLS*

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ABSTRACT

This paper presents the performance of GaAs solar cells grown on the Ge substrates, in some cases the substrate was thinned to reduce overall cell weight with good ruggedness. The conversion efficiency of 2x2cm cells under AMO reached 17.1% with the cell thickness of 6 mils. The experience gained in this structure will be used to increase GaAs cell efficiency. Also the work described forms the basis for future cascade cell structures, where similar interconnecting problems between the top cell and the bottom cell must be solved. The details include discussion of substrate properties, growth conditions of GaAs cells, and cell construction including possible substrate thinning. A discussion will follow regarding applications of the GaAs/Ge solar cell in space and expected payoffs over present solar cell technologies.

INTRODUCTION

It has been known that GaAs solar cells have higher conversion efficiency and higher radiation resistance than Si solar cells. However, GaAs solar cells are more than twice as heavy as Si cells. For space applications it is desirable that the solar cell is lightweight, have high efficiency, and high radiation resistance. In order to meet all these requirements GaAs solar cells have to be fabricated on a substrate which is not only lighter or thinner than GaAs, but also more rugged than GaAs. Both silicon and germanium were considered as the starting substrates on which the GaAs solar cell may be fabricated. Because of the huge lattice mismatch between Si and GaAs the silicon substrate was ruled out. Germanium was selected because Ge and GaAs have very close lattice constants and thermal expansion coefficients. Also, Ge is a very rugged material so that it can be thinned to reduce the overall cell weight without introducing any mechanical problem. In this paper, we present the results of p on n GaAs solar cells on n-type Ge substrates.

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CELL FABRICATION

The structure of the p on n GaAs/Ge solar cell is shown in Figure 1. The n-type Ge substrate is doped with Sb and the electron concentration is in the middle of 10^{17} cm^{-3}. The starting Ge wafer is approximately 7 mil thick and the crystal orientation is 4 degrees off the (100) direction. The heteroface GaAs/AlGaAs solar cell structure was deposited by the low pressure organometallic vapor phase epitaxy (OMVPE) technique. First an n-type GaAs buffer layer doped with Se was grown on top of the n-type Ge wafer. Then a p-type GaAs emitter and a thin p-type window layer were deposited and the p-type dopant was Zn. During the OMVPE growth the chamber pressure was 130 torr and the growth temperatures were 720 and 680°C. The 720°C was used to take advantage of the Ge auto-doping effect so that the electron concentration in the initial buffer layer was so high that it eases the electric properties at the hetero-interface between the Ge substrate and the GaAs buffer layer. This auto-doping effect was ceased by lowering the growth temperature to 680°C. The actual GaAs homojunction was grown at this temperature to obtain higher short-circuit current. The typical thickness for the buffer layer, the emitter, and the window layer is 9, 0.5, and 0.1um, respectively.

After layer growth the front p-contact made of Au/Zn and Ag were deposited onto the revealed p-emitter and the grid pattern was defined by the liftoff process. The multiple layer AR coatings made of TiO and AlO were next deposited on the window layer. At this point the GaAs/Ge structure was further thinned to 3 mils by removing Ge from the backside. Then the back n-contact made of Au/Ge, Ni, and Ag was deposited and sintered. Finally, the cell was cut into size. The entire cell fabrication sequence is shown in Figure 2.

RESULTS

Doping Profiles

The doping profile of the typical GaAs/Ge solar cell was measured using a Polaron C-V profiler. Figure 3 shows the doping profile of both the hole concentration in the emitter and the electron concentration in the buffer layer. The hole concentration was about 1.3 x 10^{18} cm^{-3}. The electron concentration was 2 x 10^{17} cm for the first 3um near the junction and it increased to 1 x 10^{18} cm^{-3} for the remaining 6um. This higher electron concentration was due to the auto-doping (out-diffusion) by Ge which is an n-type dopant in GaAs for the OMVPE growth. The difference in the electron concentration in the buffer layer was due to the growth temperatures. The growth temperature, Tg, was 720°C for the initial 6um and it was 685°C for the remaining 3um and the p-layer.

Modeling

The reason that the GaAs/Ge cell had high open circuit voltage and lower fill-factor is due to electric properties of the interface between the n-type Ge substrate and the n-type GaAs buffer layer. An experiment was performed to analyze the interface properties. An as-grown cell structure was etched in a 3:1:1 solution to remove the window layer and the p-emitter. N-type ohmic contacts were deposited and sintered on the GaAs buffer layer and the backside of the Ge substrate. The sample was cut into 5x5mm after sintering the n-contacts. A typical dark I-V characteristics of the isotype heterojunction interface is shown in Figure 4. The I-V characteristics are non-linear and the resistance of the 5x5mm sample was approximately 2 ohms near the origin. Therefore the series resistance of the isotype heterojunction between GaAs and Ge was high enough to result in low fill-factor.

Also a third terminal was made to the (n)GaAs buffer layer of a GaAs/Ge cell to evaluate the photovoltaic effect at the (n)GaAs/(n)Ge isotype heterojunction. It was found that Voc was 0.035V and that the polarity of this photovoltage agreed with that of the p/n GaAs cell. The polarity of this photovoltage suggests that the junction between the (n+)GaAs and (n)Ge be an n-type Schottky barrier. Figure 5 shows the band structure of the GaAs p/n junction and the (n+)GaAs/(n)Ge Schottky barrier. The degenerated (n+)GaAs acts as a metal on the (n)Ge semiconductor. The magnitude of the barrier height affects the collection photocurrent; i.e. Cff. The Schottky barrier height can be reduced by lowering the resistivity of the Ge substrate. It has been verified that better CFF for GaAs/Ge cells has been obtained by using low resistivity Ge wafers.

Light I-V Characteristics

The 2x2cm GaAs/Ge solar cells made on the 0.015 ohm-cm Ge substrates were tested under an AMO simulator at 28°C. Figure 6 shows the light I-V characteristics of a 2x2cm GaAs/Ge cell. The conversion efficiency of the cell was 17.1%; the open-circuit voltage 1.075V; the short-circuit current 115.9mA; and the fill-factor 0.742. The thickness of this cell was approximately 7 mils.

Table I lists the performance of the GaAs/Ge cells fabricated in the same lot. All cells have efficiency higher than 16% under AMO at 28°C. At 50% cummulative yield the cell efficiency was 16.8%; the open-circuit voltage 1.088V; the short-circuit current 115.7mA; and CFF 0.722. The thickness of these cells was about 7 mils.

Contact Integrity

The contact integrity is defined by low contact resistance, good adhesion, solderability, and weldability. The Ag-plated tabs were soldered onto the p-contact ohmic pads of a GaAs/Ge solar cell with 16% efficiency. The light I-V curves of the cell before and after soldering the tabs are shownin Figure 7. No degradation in electrical output of the cell was introduced by soldering process. The soldered tabs were pulled at 45 degrees with respect to the cell surface. The pull strength was 925 and 475 grams. The separation between the tabs and the cell was caused by divots in GaAs. Figure 8 shows the microphotograph of the large divots in GaAs after pulling off the tab on the p-contact ohmic pad. This kind of failure mode is acceptable because the pull strength was higher than 250 grams, which was the criteria for GaAs solar cells, and because the separation was due to large divots in GaAs.

Applications

It has been recognized that development of a lightweight GaAs solar cell is critical for achieving arrays with specific power approaching 300 W/kg (Ref. 1). The work presented here is a major step in approaching this type of performance. With the thin GaAs/Ge solar cell, a 50% improvement over silicon in EOL output can be realized with about the same cell weight. Table 2 outlines the relative performance of three cell technologies; silicon, gallium arsenide, and gallium arsenide on germanium. All values represent solar cells with 150 micron (6 mil) coverglasses in a 5 year, mid altitude orbit.

Further weight reduction and thermal survivability could be achieved by the use of deposited integral coverglasses. The relatively low tensile strength of standard GaAs cells inhibits use of integral covers due to cell bowing (Ref. 2). Use of a germanium substrate, with its higher strength, should allow for integral covers to be deposited on the thin GaAs cells, eliminating the need for adhesives. Further work is required in this area to ensure that the cover deposition temperature does not cause germanium diffusion into the GaAs buffer layer.

Other areas which warrant further research include fabrication and processing of the germanium substrate, larger area ($> 4cm^2$) device fabrication, and a cell interconnect process. Optimization of these processes would result in a planar solar array specific power of about 290 W/kg using present array blanket technology. This value compares to about 185 W/kg for a silicon array of the same basic design.

Use of the thin GaAs/Ge solar cells would not have to be limited to planar arrays or single junction applications. These cells could be used in concentrator arrays as well, although their advantages over conventional GaAs cells diminishes in this configuration. One remaining advantage, which could become significant, would be a reductiion in cost due to the substrate. The present cost of germanium is about half that of gallium-arsenide. Finally, the design of the thin GaAs cells lends itself well to multi junction cell applications. The materials technology developed for this cell could be applied to an AlGaAs/Ge monolithic multi-juncton cell design promising even higher efficiencies. In addition, the thin cell technology would yield a lightweight multi-junction solar cell.

CONCLUSION

In conclusion, the conversion efficiency of 2x2cm GaAs/Ge solar cells under AMO at 28°C reached 17.1% and a lot average of 16.8% has been demonstrated. It was found that the fill factor of the cell could be improved by reducing the barrier height at the isotype heterojunction between the Ge substrate and the (n) GaAs buffer layer.

This solar cell design presents many significant options for application to future space power systems. The most obvious use would be in ultra lightweight arrays, where the thin cell's high efficiency and radiation resistance would greatly improve power densitites. The GaAs/Ge solar cell could also be used in concentrators, where the biggest contribution would probably be in cell cost reduction. Additionally, the technology developed for this work represents an important step in the development of high efficiency monolithic multi-junction solar cells.

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TABLE 1

PERFORMANCE OF 2X2 cm GaAs/Ge SOLAR

Cell #	Voc (mV)	Isc (mA)	CFF (%)	Vm (mV)	EFF (%)	Yield (%)	Voc (mV)	Isc (mA)	CFF (%)	Vm (mV)	EFF (%)
12	1075	115.9	74.2	856	17.1	8.3	1075	115.9	74.2	856	17.1
5	1101	115.1	72.0	856	16.9	16.7	1088	115.5	73.1	856	17.0
2	1091	116.6	71.7	860	16.8	25.0	1089	115.9	72.6	857	16.9
6	1092	115.2	72.5	864	16.8	33.3	1090	115.7	72.6	859	16.9
7	1083	116.1	71.8	856	16.7	41.7	1088	115.8	72.4	858	16.9
4	1094	115.5	71.2	824	16.6	50.0	1089	115.7	72.2	853	16.18
1	1092	115.5	71.1	868	16.6	58.3	1090	115.7	72.1	855	16.8
9	1098	116.4	70.0	856	16.5	66.7	1091	115.8	71.8	855	16.8
11	1061	116.3	72.0	828	16.4	75.0	1087	115.8	71.8	852	16.7
10	1096	113.3	70.9	864	16.3	83.3	1088	115.6	71.7	853	16.7
3	1080	116.8	693	828	16.2	91.7	1088	115.7	71.5	851	16.6
8	1088	115.1	69.1	824	16.0	100.0	1088	115.6	71.3	849	16.6

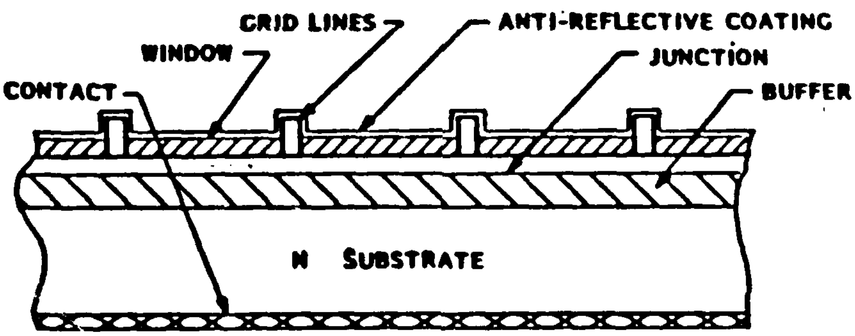
TABLE 2

COMPARISON OF SOLAR CELL TECHNOLOGY PERFORMANCE

CELL TYPE	CELL THICKNESS (MICRONS)	TOTAL WEIGHT (GRAMS)	η %	
			BOL	EOL[3]
Si	100	0.35[1]	15	5.4
GaAs	305	0.82[2]	17	9.5
GaAs/Ge	78	0.35	18.5	10.4

[1] From Ref. 2
[2] From Ref. 3

[3] EOL values based on data in Ref.4; values for GaAs/Ge cells are calculated assuming agreement with data for GaAs performance.



ELEMENT	THICKNESS (μm)	COMPOSITION	DOPANT CONCENTRATION ($\times 10^{18}$ cm^{-3})
GRID (p-CONTACT)	4.0	Ag – Au Zn Au	–
AR COATING	0.1	$Ti\,O_x/Al_2O_3$	–
WINDOW (p^+)	0.1	$Al_xGa_{1-x}As$ (Zn)	2 TO 4
JUNCTION (p)	0.45	GaAs (Zn)	2
BUFFER (n)	9	GaAs (Se)	0.2 TO 0.5
SUBSTRATE (n^+)	75	Ge (Sb)	–
n – CONTACT	3.38	Ag – Au Ge Ni Au	–

FIGURE 1

GaAs/Ge SOLAR CELL STRUCTURE

1. Thin Ge Substrates to 7-8 Mils.
2. Prepare the surface of Ge wafers.
3. Grow GaAs and AlGaAs by MOCVD technique.
4. Etch window layer.
5. Deposit front p-contacts.
6. Deposit AR coating.
7. Thin GaAs/Ge cells to 3 mils.
8. Deposit back n-contacts.
9. Cut cells to size.
10. Test

FIGURE 2

PROCESS STEPS FOR THIN GaAs/Ge SOLAR CELLS

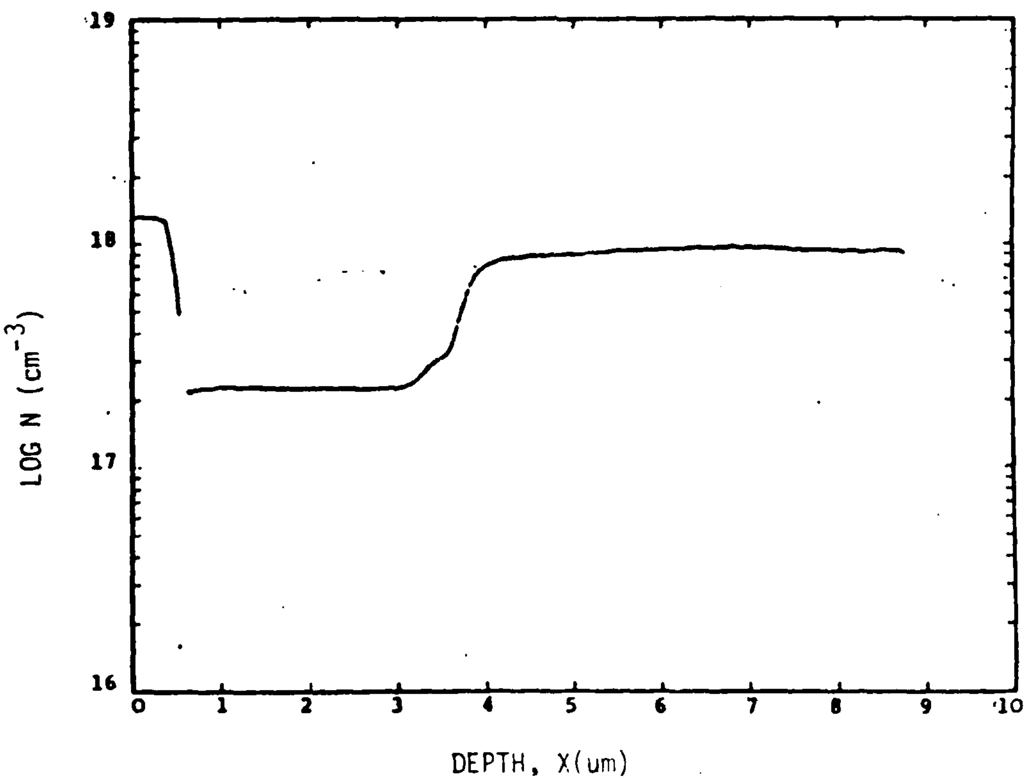


FIGURE 3

DOPING PROFILE OF A GaAs P/N JUNCTION GROWN ON A Ge SUBSTRATE

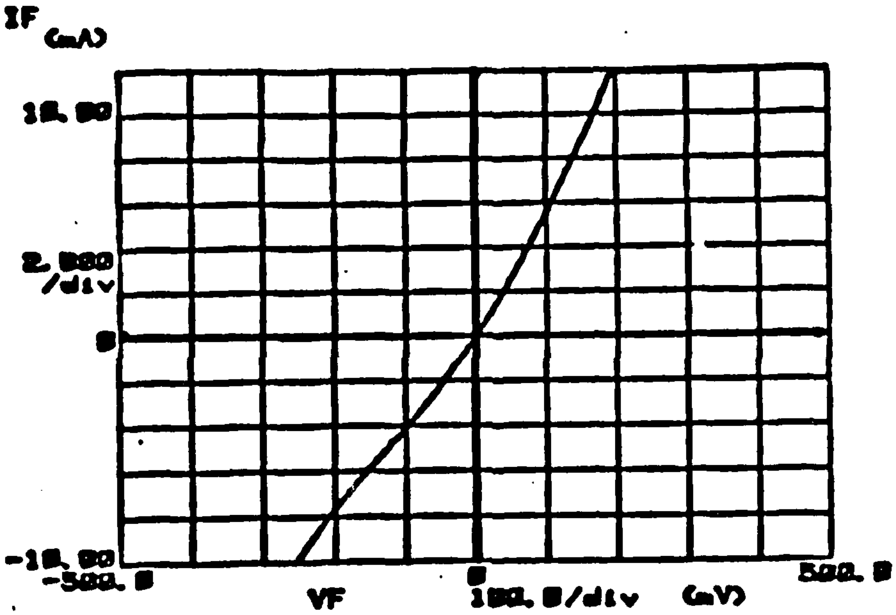


FIGURE 4

DARK I-V CHARACTERISTICS OF A (n)GaAs/(n)Ge ISOTYPE HETEROJUNCTION. THE SIZE OF THE DEVICE IS 5mm SQUARE

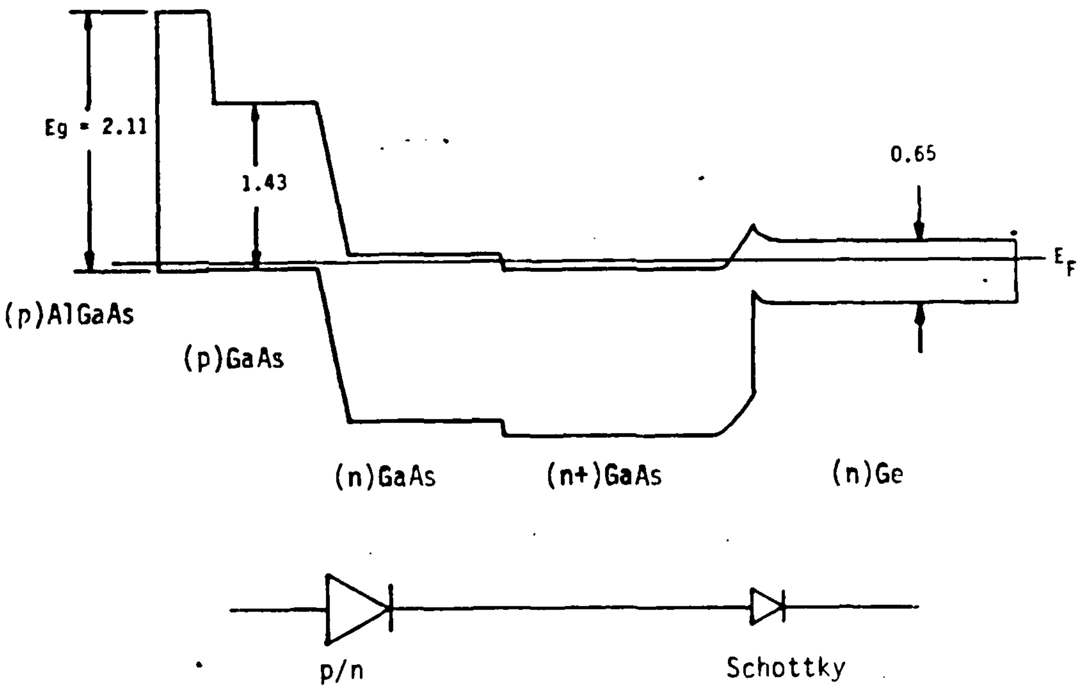


FIGURE 5

BAND STRUCTURE OF THE GaAs/Ge SOLAR CELL

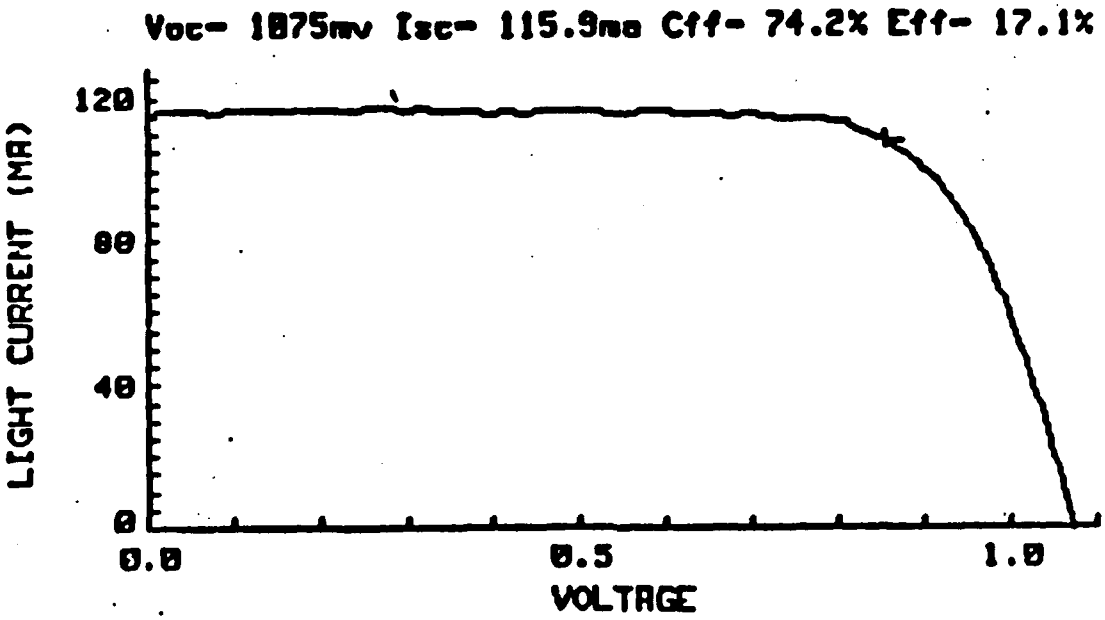


FIGURE 6

LIGHT I-V CURVES OF A 2x2cm P ON N GaAs/Ge SOLAR CELL (#12) TESTED UNDER AMO AND 28^{o}C. THIS CELL IS 6 MIL THICK.

(a) (b)

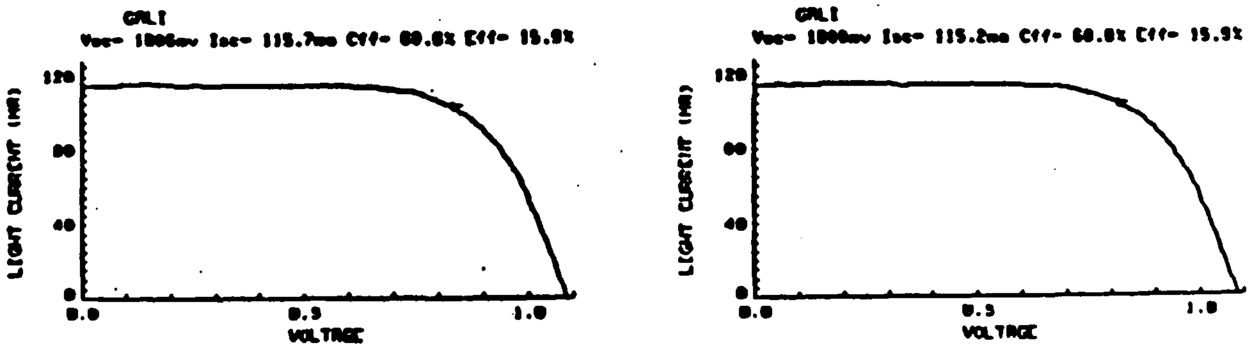


FIGURE 7

LIGHT I-V CHARACTERISTICS OF A GaAs/Ge SOLAR CELL #8 (a) BEFORE AND (b) AFTER SOLDERING TABS TO THE FRONT P-OHMIC CONTACTS.

(a) (b)

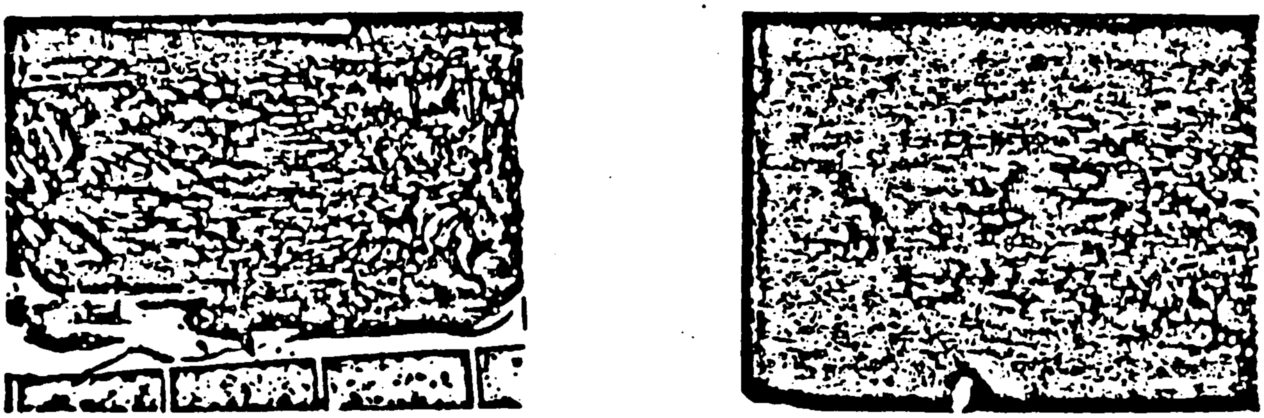


FIGURE 8

MICROPHOTOGRAPHS (50X) OF (a) THE PAD AND (b) THE TAB AFTER PULL TEST FOR CELL #8.

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